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Suitability of a mobile phone colorimeter application for use as an objective aid when matching skin colour during the fabrication of a maxillofacial prosthesis.

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Running Title: Mobile app for colour matching facial prosthetics

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Abstract

Purpose: Colour matching a facial prosthesis to human skin is very challenging. Colorimeters aid this process by adding objectivity to what is an otherwise subjective procedure. Mobile-phone colorimeter applications offer a less expensive and widely available alternative to dedicated colorimeter devices for colour measurement. There is a lack of evidence in the literature regarding the suitability of mobile-phone colorimeter applications for the development of silicone shades for facial prosthetics. The purpose of this study is to determine the suitability of a mobile-phone colorimeter application for matching natural skin colours during the fabrication of maxillofacial prostheses.

Materials & Methods: Ten pigmented maxillofacial silicone elastomer swatches were fabricated to mimic a range of different human skin tones. Colour measurements of these swatches were **recorded** using a test instrument - the mobile phone colorimeter application (RGB Colorimeter, White Marten UG, Stuttgart, Germany) and a reference instrument – the commercially available skin colour measurement device e-skin spectrocolorimeter, (Spectromatch, Bath, UK). Comparisons in **trueness** and precision of the colour measurements were made using methods previously described by Seghi *et al*. Data analysis were performed on the recorded results for each of the parameters at three distances (25mm, 30mm &35mm) of the test instrument from the target against both a black and a white background.

Results: The **trueness** of the mobile phone colorimeter application relative to the colorimeter device varied depending on the distance from the target and the background colour. The relative **trueness** of the colour difference measurements fell just within the documented upper threshold of acceptable limits of colour difference (ΔE 3.0 - 4.4). The calculated **precision** of the CIE L*a*b* and ΔE measurements of the mobile phone colorimeter application was good, with the latter being well within the documented acceptable limits.

Conclusions: Based on the findings it was concluded that a mobile phone colorimeter application would be a suitable aid in objectifying the process of colour matching a silicone maxillofacial prosthesis. Further investigation into image calibration to improve **trueness** and the control of variables such as background noise, uniformity of illumination and measuring distance is required.

Keywords: Maxillofacial Prosthetics, Colour Measurement, Colorimeter, Mobile Phone Application.

Introduction:

Maxillofacial defects occur as a result of congenital anomalies, trauma or tumour resection.[1] Alloplastic or autogenous reconstruction is suited to cases with small, less complex defects, particularly those involving mobile soft tissues.[2] Prosthetic rehabilitation is indicated for large defects or where surgical procedures may not provide predictable functional or aesthetic results.[1] Due to their favourable characteristics silicone elastomers have become the material of choice for the construction of facial prostheses. They are chemically inert, thermally stable, have low toxicity, display adequate tear strength and flexibility and can be processed to resist absorption, preventing bacterial growth and allowing cleaning procedures.[3,4] Another major advantage of these materials is that they can be stained intrinsically and extrinsically to match the patients natural skin colour and impart a lifelike appearance.[3]

The most common method of colouring silicone maxillofacial prosthetics is the "trial and error" method.[5] This chair-side process involves the gradual addition of pigments to the silicone elastomer. The resultant colour is visually assessed against the patient's skin and adjusted until an acceptable colour match is achieved. This process is technique sensitive, time consuming, and the trueness of the resultant colour match is dependent on variables such as translucency, metamerism and the subjective nature of human colour perception.[6]

Colorimeters are capable of producing reliable and reproducible colour measurements, thus removing potential variables involved in visual colour assessment.[7] A light source illuminates the skin, and the intensity of the light re-emitted from the skin is analysed and defined as tristimulus values based on a 3D colour space, such as the Commission International de l'Eclairage (CIE) L*a*b* colour space.[8,9] Human facial skin can be measured truly and precisely using these devices.[10]

Colorimetric technology is currently utilised to obtain skin colour readings in the clinical treatment of maxillofacial prosthetic patients e.g. e-skin (Spectromatch, Bath, UK).[11]

Colour measurements are compared and matched to those of colours stored in a digital library with known exact colour recipes. These colour recipes can then used to produce maxillofacial prostheses that closely match the patients' natural skin colour.[11] Such systems are based on specialised colorimeter devices that are relatively expensive and not widely available.

Mobile phones with inbuilt digital cameras are ubiquitous in modern society.[12] The technical capabilities of these devices has evolved rapidly, providing almost universal access to a portable, network connected visual sensor.[12] There are a variety of mobile phone colorimeter software applications currently available which provide simple, cheap and readily available colour measurements. Mobile phone colorimeter applications have proved effective measuring tools for functions as diverse as detecting the chlorine content in water and the presence of tetracycline in milk.[13,14]

Mobile phone colorimeter applications utilise the devices camera lens, photo sensor, computer software and visual display in order to obtain a colour measurement. Light passes through the lens and hits the sensor, which breaks the light up into millions of tiny "dots" of digital data, called pixels, that contain raw colour information.[15] The software application uses the raw colour data obtained from each pixel and transforms it into device independent colour coordinates, such as CIE L*a*b* values. This data transformation is called camera characterisation, and the efficiency of this process, as well as the camera quality, will dictate the trueness of the colour measurements given.[16]

At present, there is a lack of evidence in the literature regarding the use of mobile phone colorimeter applications in the field of maxillofacial prosthetics. Such an application has the potential to provide a cheaper, more easily accessible, and widely available aid in the development of silicone shades for facial prosthetics than currently available skin colour measurement systems. The aim of this study is to determine the suitability of a mobile phone colorimeter application as an objective aid in matching skin colour during the fabrication a maxillofacial prosthesis.

Materials and Methods

Two sets of colour measurements of 10 skin coloured maxillofacial silicone specimens were obtained, one using a selected mobile phone colorimeter application and the other using a commercially available maxillofacial colorimeter device, whose measurements were accepted as being correct. To permit all colour measurements to be taken at known repeatable angle and distance from each specimen a calibration jig was constructed. The reproducibility of the result was assessed by repeating each measurement 3 times. Measurements were obtained for each specimen positioned over a white and black background respectively. These measurements were repeated for the test instrument placed in the jig at 3 distances from the target point, 25mm, 30mm and 35mm.

Colour differences between the instrument measures were evaluated using the methods previously described by Seghi et al. (1989)[17] to determine the trueness and precision of the test instrument. Its suitability for use as an aid when colour matching maxillofacial silicone was then determined by comparison of the values of trueness and precision against documented acceptable colour difference thresholds. To examine the effects of background colour and distance on the performance of the test instrument, a two-way repeat measures analysis of variance was performed on the data.

Specimen Fabrication

Ten maxillofacial silicone swatches of varying colours were prepared using a two-part maxillofacial platinum silicone elastomer (Z004 Silicone Elastomer, Lot B17C, Technovent Ltd, Bridgend, South Wales, UK). To achieve a mixture of uniform colour and opacity, each swatch was coloured using intrinsic maxillofacial pigments (Technovent Ltd, Bridgend, South Wales, UK) incorporated thoroughly in a centrifuge. The un-polymerized swatches were packed into a mould with 10 segments of uniform dimensions (40 x 25 x 10mm^3) (Fig 1) and polymerised in an oven as per manufacturer's instructions. Once polymerised, a permanent marker was used to make a black dot in one corner of each swatch so its orientation in the jig could be verified for each measurement.

The Calibration Jig

To permit all colour measurements to be taken at a set repeatable angle, distance and at the same point on each specimen, a calibration jig was constructed (Fig 2). The jig consisted of a platform, capable of movement in a vertical direction, onto which each test specimen was placed. A 4mm high lip around the outer edge of the platform was used to hold the test specimens in position. A target mark on the platform allowed precise alignment of the measurement instrument. Two pieces of card, one black and one white, were inserted into the platform to alter the background colour as required. Suspended above the platform, via a roofing bolt, was a device holder into which the measuring devices were placed. The device holder had an adjustable edge so it could be adapted to fit the dimensions of each device. The jig had two test positions; with the specimen laying horizontally (Fig 2a) for taking measurements with the contact reference instrument, and with the specimen laying vertically (Fig 2b) for taking measurements with the non-contact test instrument.

The Reference Instrument

The instrument used to obtain the reference measurements was the e-skin spectrocolorimeter (Spectromatch, Bath, UK). The e-skin is a handheld, contact measuring device that records colour measurements in CIE L*a*b* coordinates relative to standard illuminant D65 and 10° observer angle. The device has an independent tri-directional 25 LED light source and a measuring area that can be adjusted between 4 and 8mm. During operation the device is held in direct contact with the specimen being measured. Colour measurement is achieved when light reflected from the specimen as it is illuminated by the light source passes through the measuring aperture to a set of filtered photo detectors. The devices skin colour measurements are matched with colour recipes of more than 20,000 skin tones stored in its digital library. The colour recipe is instantly displayed on its screen and the clinician can then accurately weigh out the formulations required to fabricate the prosthesis.

The Test Instrument

The test colour measurements were obtained using the Mobile phone colorimeter application – RGB Colorimeter (White Marten UG, Stuttgart, Germany) – installed on a smartphone (iPhone 5s, Apple, Cupertino, USA). The RGB mobile phone colorimeter application is a non-contact measuring instrument that relies on the ambient light to illuminate the scene. Light passes through the mobile phones camera lens onto the photo sensor, which breaks the light up into millions of tiny “dots” of digital data. These “dots” of data are called pixels, and they contain the raw colour data. The colorimeter application software transforms the raw colour data from each pixel to obtain device independent coordinates, and it display these measurement on the device’s screen in a variety of different formats including CIE L*a*b* coordinates.

This particular application was selected over all the other freely available colorimeter applications in the apple “app store” as it was one of only two such applications that gave the colour measurements in CIE L*a*b* colour coordinates, the same as the reference instrument. Of these two applications, only the RGB colorimeter’s interface featured alignment crosshairs (Fig 3) that facilitated alignment of the device over the target mark on the test jig. This allowed repeatable positioning of the mobile phone device in the test jig so that all measurements could be taken at the same point on each swatch.

Data Collection

Six colour measurements were taken for each swatch using the e-skin colorimeter, three against the black background and three against the white background. The colorimeter was recalibrated prior to every measurement taken, and the device realigned over the target point using reference marks indicating the centre of the aperture (Fig 4a). Once aligned, the background colour card (white or black) was placed into the tray and the relevant swatch placed in position with the orientation mark facing away from the measuring device against the lower left corner of the tray. The tray was then raised until the swatch came into contact with the aperture on the colorimeter (Fig 4b) and the colour measurement was then obtained.

As the mobile phone application used was a non-contact measurement device, all measurements were taken in a Munsell 8 grey light box, under D65 fluorescent illumination (Fig 5a & b). 18 colour measurements were taken for each swatch, three measurements against the black background and three against the white background, repeated 3 times for 3 different distances between the cameras lens and the swatch, 25mm, 30mm and 35mm respectively. The mobile phone was repositioned between each measurement and the crosshairs on the application screen aligned with the target point on the test jig before placing the relevant background colour card and swatch. All measurements were taken at 25mm distance between the phones camera lens and the swatch before adjusting the platform so the distance became 30mm and finally 35mm for the final set of measurements.

Data Analysis

The colour measurements obtained were evaluated using methods previously described by Seghi *et al.*[17] and using the CIEDE2000 colour difference formula[18] to calculate the colour difference (ΔE) values. The trueness of the test instrument was evaluated in 2 ways; (1) The instruments ability to obtain the colour specification in absolute colorimetric terms i.e. the absolute trueness (ΔE_{Abs}), was calculated from the mean CIE L*a*b* values obtained from the measurements made with the reference colorimeter and the mean values obtained from the measurements made with the mobile phone colorimeter app. (2) The trueness of the colour difference measurements i.e. the relative trueness (ΔE_{Rel}) was calculated from the mean colour difference determined from the reference colorimeter data and the mean of the corresponding differences obtained from the mobile phone colorimeter app measurements. In both cases low ΔE values correspond to instruments with high trueness.[17]

The precision of the test instrument is related to the repeatability of its colour measurements, and this was evaluated in 2 ways; (1) The errors associated with the precision of the CIE L*a*b* measurements, absolute precision (ΔE_{LAB}), were calculated from the mean CIE L*a*b* values obtained from the three measurements made with the mobile phone colorimeter app on a given sample, and the corresponding values reproduced from an individual measurement of that sample. (2) The errors associated with the precision of the colour difference measurements, relative precision (ΔE_{CD}), were calculated using the mean colour difference between two samples as determined from the three measurement sets generated by the mobile phone colorimeter app and the calculated colour difference between the same two samples, as determined from an individual colour set obtained using the test instrument. In both cases a low ΔE values represent good precision.[17]

The mean and standard deviation of the trueness and precision colour difference values obtained for the test instrument at the 3 distances, 25mm, 30mm and 35mm, against both black and white backgrounds were calculated for comparison. A two-way repeat measures analysis of variance was performed for each of the parameters to determine if distance from the target and background colour had a significant effect on the colour measurements ($p<0.05$).

Results

The mean and standard deviation (sd) for the colour difference values (ΔE) calculated for absolute and relative trueness and precision are reported (Table 1). A summary of values generated for the measurement of absolute trueness (ΔE_{Abs}) for measurements taken at all distances from the target specimen against both backgrounds is shown (Table 2). Measurements taken at 35mm against the white background showed the lowest mean ΔE value of absolute trueness. The analysis of variance demonstrated that the background colour and the distance from the target had a significant effect on the absolute trueness of the test instrument ($p < 0.05$) but there was no interaction between the two groups. Pairwise comparisons of the values obtained at the 3 distances from the target showed a statistically significant difference in absolute trueness ($p^b < 0.05$) between the 25mm and 30mm groups, and the 25mm and 35mm groups, but no statistically significant difference between the 30mm and 35mm groups.

The values generated for the measurement of relative trueness (ΔE_{Rel}) revealed that the mean ΔE values were significantly lower than the recorded values of absolute trueness (Table 3). The lowest ΔE values were again recorded at 35mm from the target against a white background. Analysis of variance testing demonstrated that both background colour and the distance from the target had a significant effect on the relative trueness of the test instrument ($p < 0.05$). As with absolute trueness, there was a statistically significant difference in relative trueness ($p^b < 0.05$) between the 25mm and 30mm groups, and the 25mm and 35mm groups, but no statistically significant difference between the 30mm and 35mm groups.

The colorimeter app displayed similar absolute precision (ΔE_{LAB}) of the CIE L*a*b* measurements at all distances against both background colours (Table 4). The distance from the target had a significant effect on the absolute precision of the test instrument ($p < 0.05$) as demonstrated by analysis of variance, but the background colour had no significant effect on absolute precision. Pairwise comparisons showed a statistically significant difference in absolute precision (p^b <0.05) between the 30mm and 35mm groups, but no significant difference between the 25mm and 30mm groups, and 25mm and 35mm groups.

The analysis of variance demonstrated that the background colour and the distance from the target had a significant effect on the relative precision (ΔE_{CD}) of the test instrument (p <0.05) (Table 5). Pairwise comparisons revealed a statistically significant difference in relative precision (p^b <0.05) between the 30mm and 35mm groups, but no significant difference between the 25mm and 30mm groups, and 25mm and 35mm groups.

Discussion

Analysis of the performance of colour-measuring devices in terms of the errors associated with the measurements made provides information that may guide the development of future applications and clinical instrumentation.[17] The precision of a measurement instrument refers to its ability to give the same readings for a given sample over a period of time, while trueness relates the performance of the instrument compared to a set of readings shown to be true or correct.[19]

The measurement of colour in absolute terms is not possible however, as measured values differ with the conditions of measurement in ways which cannot be said to be right or wrong.[19] For this reason it is convenient to take as a working definition of trueness the degree of conformance to results from a widely used reference instrument.[19] The results obtained in this study demonstrate that while a mobile phone colorimeter application is not as accurate as a dedicated colorimeter device, it is capable of producing precise colour measurements that fall within acceptable colour difference thresholds.

Systematic and Random Errors

Errors in the colour measurement process can be either systematic or random. Systematic errors can arise from factors such as inaccurate calibration techniques, filter design and variations in measuring geometries, and they generally tend to affect the trueness of the instrument.[17] Random errors result from factors such as background noise and sample preparation and tend to affect the precision of the instrument.[17] Systematic errors are harder to detect and manage so trueness between colour measuring devices is subject to greater variability.[17] Systematic errors will have a greater effect on the absolute trueness (ΔE_{Abs}) of the instrument, even under controlled conditions, therefore, the relative trueness (ΔE_{Rel}), which is a measure of the instruments ability to asses colour difference between objects accurately, is a much more meaningful measure.[17] Differential measurements greatly reduce the effects of systematic errors and is the most effective method of colorimetric analysis.[17]

Perceptibility and acceptability thresholds

In this study the lower the values of ΔE recorded for the measures of absolute trueness (ΔE_{Abs}), relative trueness (ΔE_{Rel}), absolute precision (ΔE_{LAB}) and relative precision (ΔE_{CD}), the higher trueness or precision the instrument demonstrates.[20] The test instruments performance can be evaluated by viewing these values in relation to observer perceptibility and acceptability thresholds for identifying colour differences in maxillofacial silicones, however studies in this area are limited. Based on the response from 90 colour-normal observers, Leow *et al.* (2006)[21] determined the perceptibility and acceptability colour-difference thresholds in light and dark skin-coloured maxillofacial elastomers were ΔE = 0.8 and ΔE = 1.8 for the fair specimens and ΔE = 1.3 and ΔE = 2.6 for the dark specimens respectively. Paravina *et al.* (2009)[22], in a study where 15 pairs of light skin-coloured silicone elastomer specimens and 15 pairs of dark skin-coloured specimens were evaluated by 45 observers under controlled conditions, found perceptibility and acceptability thresholds for light specimens were ΔE = 1.1±0.7 and ΔE = 3.0±2.1, respectively. Corresponding values for dark specimens were ΔE = 1.6±1.2 and ΔE = 4.4±3.1, respectively.

More evidence is available on the perceptibility and acceptability thresholds of dental materials. Douglas *et al.* (2007)[23] recorded the observations of 28 dentists on the perceptible and acceptable colour differences between denture teeth in a clinical setting and predicted the ΔE at which 50% of the observers (50/50 perceptibility) could perceive a colour difference was 2.6ΔE and the predicted ΔE at which 50% of the subjects would remake the restoration (clinically unacceptable colour match) was 5.5ΔE. Ghinea *et al.* (2010)[24] studied the 50/50 perceptibility and acceptability ΔE thresholds of dental ceramics and found them to be 1.30ΔE and 2.25ΔE respectively, whereas Paravina *et al.* (2015)[25] identified the perceptibility and acceptability thresholds for dental ceramics to be 0.8ΔE and 1.8ΔE respectively.

There is some degree of variation between the perceptibility and acceptability thresholds documented and Seelaus *et al.* (2011)[26] identified a "need to improve our understanding of the relationship between the objective (computer-driven) and subjective (clinical opinion) of what is considered an 'acceptable' colour match". When investigating technology versus clinical perception of silicone prostheses, Seelaus *et al.* demonstrated that agreement between objective and subjective measures of colour were not always evident.[26] These discrepancies were attributed to translucency and pigment loading of the silicone samples tested and can be explained by variations in measurement trueness associated with scattering, absorption, and edge loss.[26,27]

In this study, as expected, the highest mean ΔE values for all distances against both black and white backgrounds were recorded for absolute trueness (Fig 6), the overall mean ΔE being 13.44 ± 5.67. The values recorded for relative trueness, to assess colour difference between objects, were significantly lower (Fig 7), the mean ΔE value being 4.17 ± 2.81. This value is just within the acceptable limit for dark skin-coloured specimens as reported by Paravina *et al.* (2009).[22]

The ΔE values for absolute precision and relative precision were much lower than the trueness measurements, the overall mean values being ΔE = 1.95 ± 1.11 and ΔE = 0.97 ± 1.21 respectively. Both values are well within the acceptable upper thresholds of all the referenced studies.

Image Calibration

It is not possible to retrieve accurate colour measurements from un-calibrated images taken with un-calibrated cameras.[28] It is possible however, to estimate skin-colour measurements by using appropriate colour information in the form of a calibrated target present in the scene.[28] Marguier *et al.* (2007)[28] demonstrated that if the object of interest is imaged together with a reference target, the target colour values can be extracted and used to compute a colour correction matrix that can be applied to the entire image. Using this method, it is possible to consistently classify skin tones using un-calibrated images taken with un-calibrated cameras by colour correction using targets consisting of patches characteristic of the range of human skin tones.[28] According to Marguier *et al.* with this system skin tones can theoretically be estimated with an error of $\Delta E < 1$.[28] The mobile phone colorimeter application used in this study demonstrated good precision and the development of a similar application used in conjunction with reference targets to classify skin tones is an area worthy of further investigation.

Background Colour

Analysis of the data showed that the background colour, black or white, had a significant influence on the absolute trueness, relative trueness and relative precision of the colour measurements obtained with the test instrument. The measurements obtained against the white background were more accurate than those obtained against the black background. Vazquez-Corral *et al.* (2014)[29] state that errors in the characterisation *i.e.* the difference between the target and estimated CIE L*a*b* values, is dependent on the sensor sensitivity of the camera, the reflectance spectra of the objects in the scene and the illumination of the scene.

The e-skin colorimeter is a contact measuring device with an independent tri-directional 25 LED light source and a measuring area that can be adjusted between 4 and 8mm.[30] The mobile phone colorimeter application is a non-contact measuring device and relies on the ambient light to illuminate the scene. The iPhone 5s camera has an equivalent horizontal field of view of approximately 29mm resulting in a much larger measuring area. The wider field of view of the mobile phone camera could explain the effect of background colour on the trueness of the colour measurements obtained with the colorimeter application. It may be possible to improve trueness by obtaining all colour measurements against a standard uniform neutral coloured background with a calibrated reference target colour present in the scene to enable colour correction of the image. The wider field of view of the mobile phone colorimeter application also has benefits for obtaining skin colour measurements as, due to the limited field of view of contact-type colour devices, measurement of heterogeneous surfaces can produce unrealistic colour values.[5]

Distance from the target

The distance between the camera lens and the target, 25mm, 30mm or 35mm, had a significant on influence on the both the trueness and precision of the CIE L*a*b* and ΔE values obtained using the mobile phone application. The effects of distance from the target on the trueness and precision of the test instrument measurements could be attributed to a number of factors such as background noise, focal length of the camera and the uniformity of illumination. Background noise from the surrounding environment will be reduced the closer the camera gets to the target. If the camera is too close to the object however, it will lose focus on the object and the device will obscure the ambient light illuminating the object being measured. The iPhone 5s has a fixed focal length of approximately 29mm. When obtaining colour measurements with a digital camera, uniformity of illumination of both the sample and the sensor plane is important in order to achieve correct colour reproduction.[15] Complete even illumination is never achieved but variation should be reduced as much as possible.[15] Uniformity of illumination due to the presence of shadows and glare from the objects surface can be affected by the distance between the camera and target.

The lowest mean ΔE values for absolute and relative trueness for the test instrument in this study were recorded at a distance 35mm from the target against the white background, 8.44 ± 4.4 and 2.04 ± 1.45 respectively, whereas the lowest mean ΔE values for absolute and relative precision were recorded at 30mm from the target against the black background, 1.32 ± 0.65

and 0.61 ± 0.42 respectively. The data analysis showed that there was no statistically significant difference between the trueness of the measurements obtained at 30mm and 35mm from the target but there was a statistically significant difference between the measurements taken at 25mm and the other two groups. This suggests that the mobile phone must be held at a distance of more than 25mm in order to obtain a true colour measurement. Further investigation is required to determine the optimum distance between the target and the lens in order to obtain the truest and most precise colour measurements.

Conclusion

Accurately colour matching silicone maxillofacial prostheses to patients skin colour is a difficult procedure, not least due to the subjective nature of human colour vision. This has led to the development of instrumentation and computerised colour formulation systems that objectify the colour matching process through the use of colour measurement devices. These systems attempt to improve trueness and efficiency of the colour matching process using dedicated spectrophotometer and colorimeter devices, which are expensive and not widely available. Mobile phone colorimeter applications have the potential to provide cheap and accessible skin colour measurements to aid in the process of colour matching a silicone maxillofacial prosthesis.

Measures of trueness and precision obtained in this study demonstrate that the trueness of the colour measurements obtained with the mobile phone colorimeter application compared to those obtained with the dedicated colorimeter device were not ideal however, the precision of the colour measurements obtained with the test device was much better and fell within the documented threshold of acceptability of colour difference. Based on these results it may be concluded that a mobile phone colorimeter application would be a suitable aid in objectifying the process of colour matching a silicone maxillofacial prosthesis.

Improvements in trueness of the colorimeter application might be achieved through the use of a reference colour target to colour correct the images when obtaining the colour measurement. Using this method, the colorimetric data is contained in the image and the colour measurements made are not device dependent so can be taken using a variety of different mobile phone devices. Further investigation into the control of variables such as background noise, uniformity of illumination and measuring distance is required.

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Tables:

Table 1. Mean ΔE values obtained for Absolute Trueness (ΔE_{Abs}), Relative Trueness (ΔE_{Rel}), Absolute Precision (ΔE_{LAB}), and Relative Precision (ΔE_{CD})

	ΔE_{Abs} ± sd	ΔE_{Rel} ± sd	ΔE_{LAB} ± sd	ΔE_{CD} ± sd
Mean Black Background	15.67 ± 5.25	4.88 ± 2.75	2.19 ± 1.32	0.98 ± 1.46
Mean White Background	11.21 ± 5.26	3.46 ± 2.71	1.71 ± 0.82	0.96 ± 0.89
Mean Total (Black & White)	13.44 ± 5.67	4.17 ± 2.81	1.95 ± 1.11	0.97 ± 1.21

Table 2. Assessment of the Absolute Trueness (ΔE_{Abs})

Background Colour	Black	White
Distance from target	Mean ΔE_{Abs} ± sd	Mean ΔE_{Abs} ± sd
25mm	17.89 ± 5.02	15.03 ± 4.98
30mm	15.37 ± 4.03	9.09 ± 4.0
35mm	13.74 ± 6.13	8.44 ± 4.4

Statistical Analysis (two-way repeat measures ANOVA)

Group	Sum of Squares	df	Mean Square	F-ratio	P
Background Colour	297.923	1	297.923	36.486	.000
Distance	322.604	2	161.302	22.853	.000
Interaction	26.035	2	13.018	3.305	.06
Error	70.907	18	3.939		

Pairwise comparisons between distances (Bonferroni)

Groups	Mean Difference	Std. Err	P^b
25mm - 30mm	3.96	.738	.001
25mm - 35mm	5.506	.682	.000
30mm - 35mm	1.546	1.053	.528

b. Adjusted for multiple comparisons: Bonferroni

Table 3. Assessment of the Relative Trueness (ΔE_{Rel})

Background Colour	Black	White
Distance from target	MeanΔE_{Rel} ± sd	MeanΔE_{Rel} ± sd
25mm	5.44 ± 2.94	5.56 ± 3.01
30mm	4.81 ± 2.67	2.67 ± 1.86
35mm	4.40 ± 2.61	2.04 ± 1.45

Statistical Analysis (two-way repeat measures ANOVA)

Source	Sum of Squares	df	Mean Square	F-ratio	P
Background Colour	174.365	1	174.365	34.662	.000
Distance	143.775	2	71.888	21.154	.000
Interaction	55.332	2	27.666	18.498	.000
Error	131.615	88	1.496		

Pairwise comparisons between distances (Bonferroni)

Groups	Mean Difference	Std. Err	P^b
25mm - 30mm	1.220	.288	.000
25mm - 35mm	1.741	.305	.000
30mm - 35mm	.521	.224	.074

b. Adjusted for multiple comparisons: Bonferroni

Table 4. Assessment of the Absolute Precision (ΔE_{LAB})

Background Colour	Black	White
Distance from target	MeanΔE_{LAB} ± sd	MeanΔE_{LAB} ± sd
25mm	2.3 ± 0.86	1.59 ± 0.84
30mm	1.32 ± 0.65	1.51 ± 0.88
35mm	2.95 ± 1.71	2.04 ± 0.71

Statistical Analysis. Two way repeat measures ANOVA

Source	Sum of Squares	df	Mean Square	F-ratio	P
Background Colour	3.379	1	3.379	2.433	.153
Distance	11.712	2	5.856	10.956	.001
Interaction	3.453	2	1.726	2.244	.135
Error	13.845	18	.769		

Pairwise comparisons between distances (Bonferroni)

Groups	Mean Difference	Std. Err	P[b]
25mm - 30mm	.572	.254	.204
25mm - 35mm	-.555	.205	.073
30mm - 35mm	-1.082	.232	.004

b. Adjusted for multiple comparisons: Bonferroni

Table 5. Assessment of the Relative Precision (ΔE_{CD})

Background Colour	Black	White
Distance from target	MeanΔE_{CD} ± sd	MeanΔE_{CD} ± sd
25mm	1.36 ± 2.33	1.17 ± 0.91
30mm	0.61 ± 0.47	0.67 ± 0.55
35mm	0.98 ± 0.77	1.05 ± 1.07

Statistical Analysis. Two way repeat measures ANOVA

Source	Sum of Squares	df	Mean Square	F-ratio	P
Background Colour	3.862	1	3.862	7.042	.011
Distance	6.451	2	3.226	6.15	.003
Interaction	4.048	2	2.024	3.73	.028
Error	47.754	88	.543		

Pairwise comparisons between distances

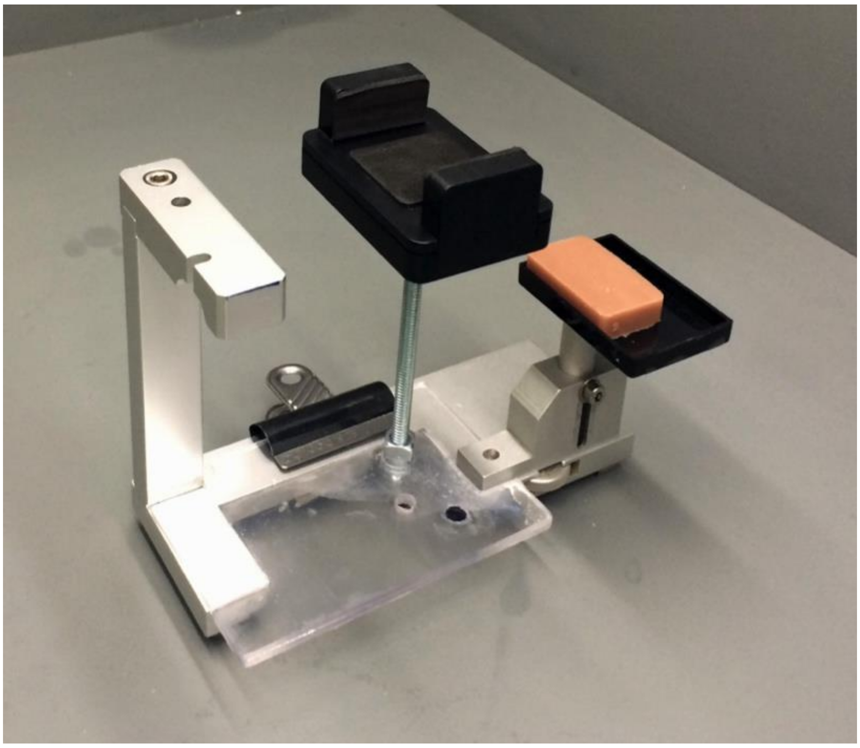
Groups	Mean Difference	Std. Err	P^b
25mm - 30mm	.163	.097	.298
25mm - 35mm	-.214	.129	.310
30mm - 35mm	-.377	.095	.001

b. Adjusted for multiple comparisons: Bonferroni

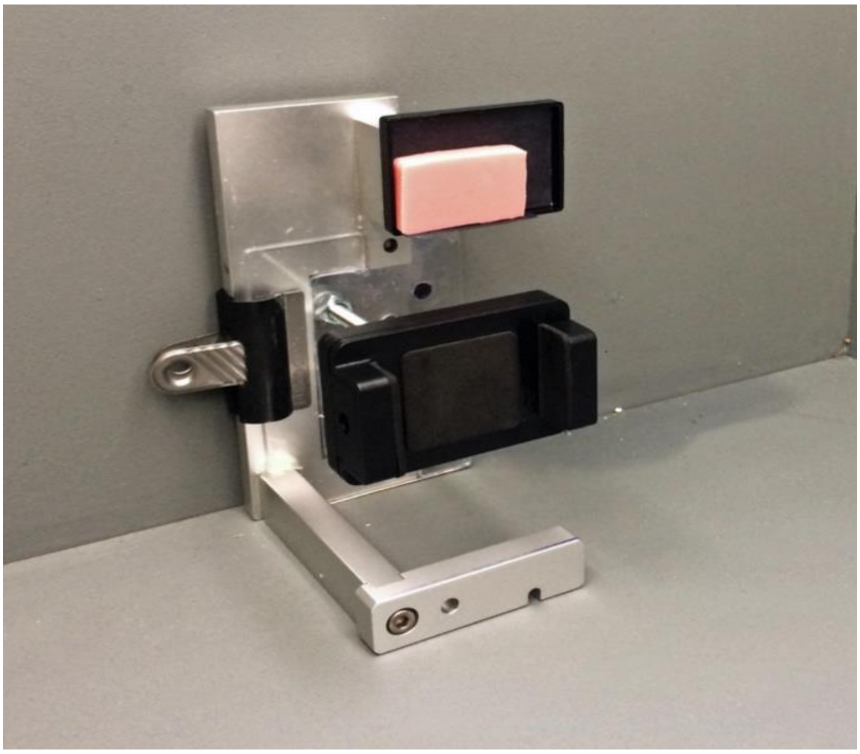
Figures:

Figure 1. The 10 coloured silicone elastomer swatches.

Figure 2. The Calibration Jig. a) Horizontal position for measurements with the contact reference instrument. b) Vertical position for measurements with the non-contact test instrument.



a



b

Figure 3. The RGB colorimeter app interface

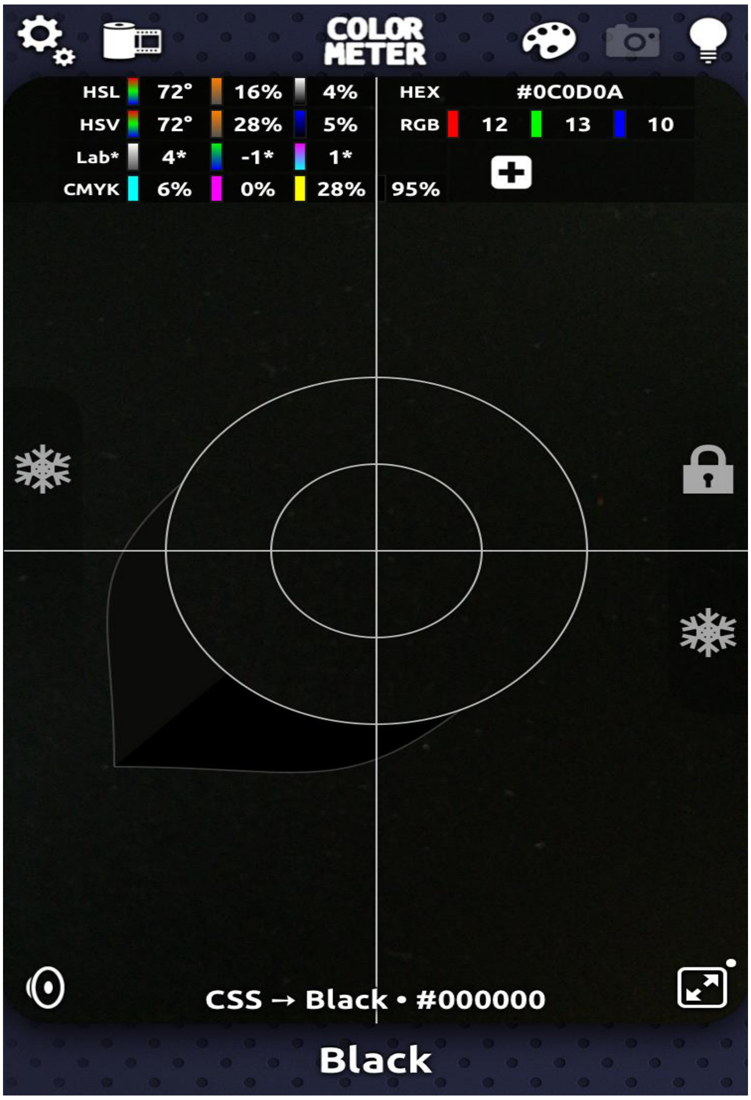
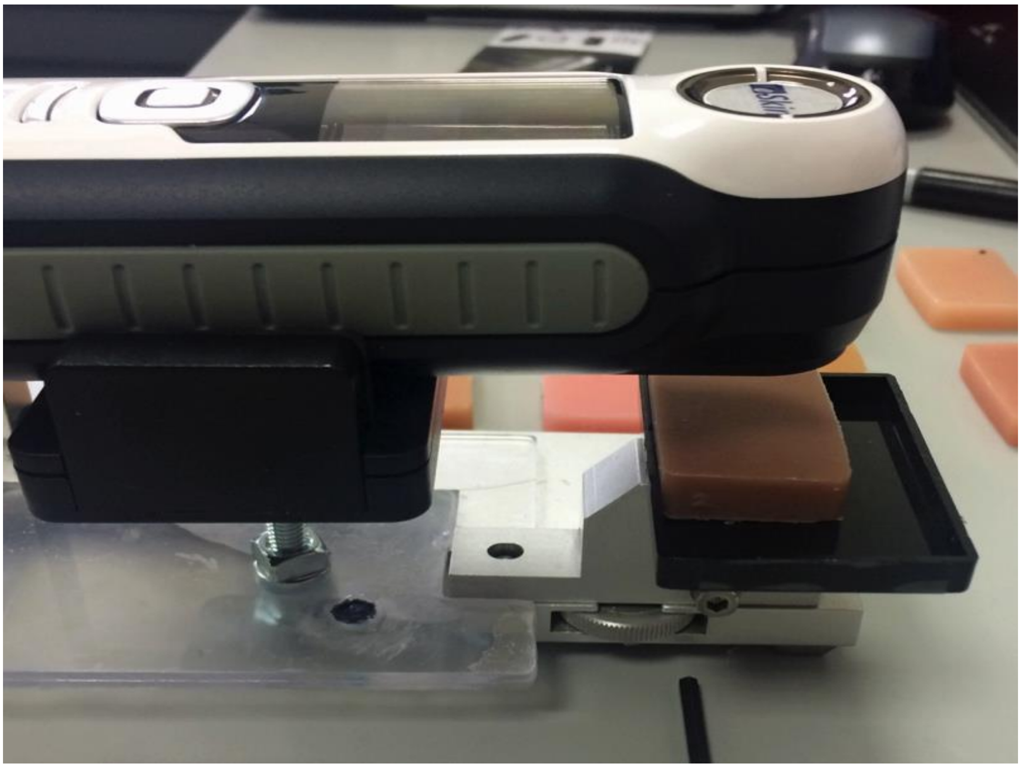


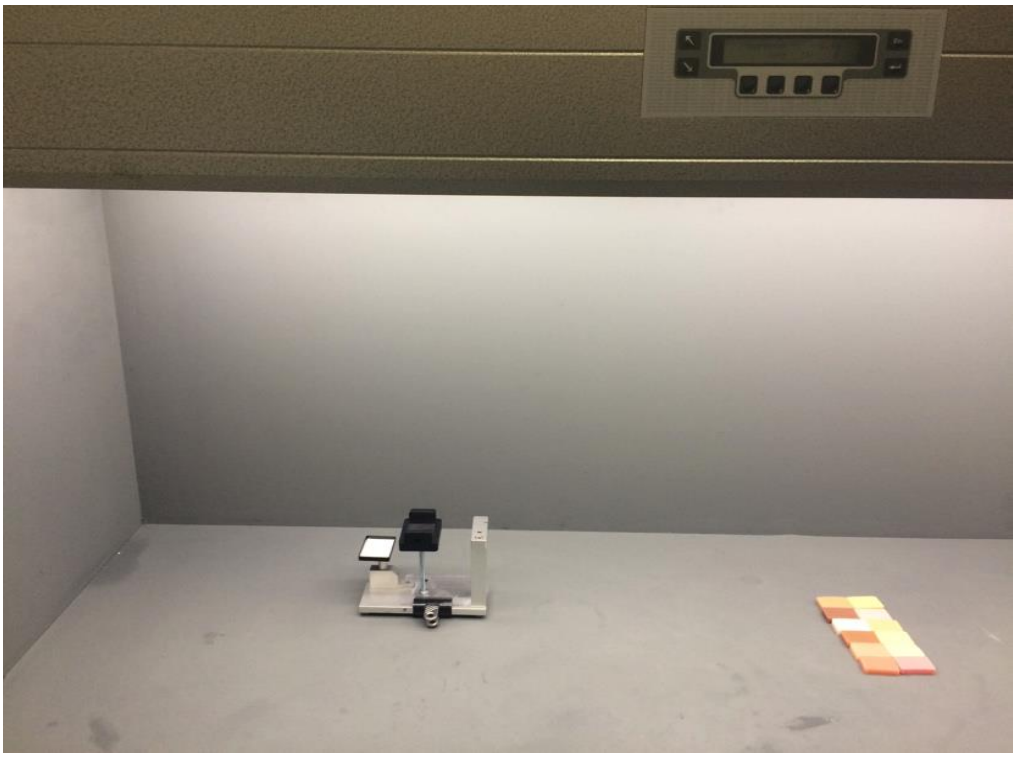
Figure 4. Setting the eskin Colorimeter in the calibration jig **a)** the instrument aligned over the target point on the jig **b)** the swatch is placed in the jig and the platform in a raised position so the specimen contacts the aperture.

a



b

Figure 5. a) Munsell 8 grey light box. b) Mobile phone set in the calibration jig



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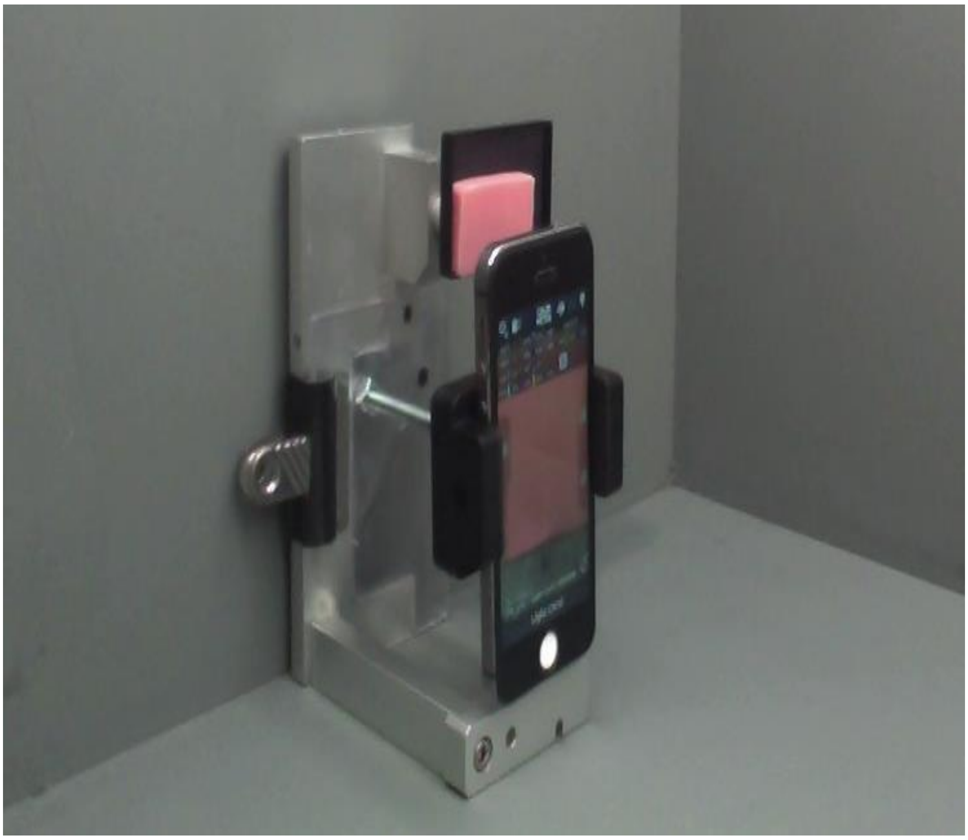

B

Appendices:

Appendix 1. CIE L*a*b* colour measurements obtained with the reference instrument – eskin spectrocolorimeter (Spectromatch, Bath UK) against **a)** black and **b)** white background.

a) e skin colour measurement CIE L*a*b* values against black background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	55.54	3.98	17.50	55.54	3.98	17.50	55.54	3.98	17.50
2	43.03	9.01	14.52	43.03	9.01	14.52	43.03	9.01	14.52
3	77.26	3.30	9.30	77.26	3.30	9.30	77.26	3.30	9.30
4	44.11	7.57	16.89	44.11	7.57	16.89	44.11	7.57	16.89
5	67.18	7.83	22.42	66.10	7.92	23.52	66.10	7.92	23.52
6	66.42	17.17	8.97	66.42	17.17	8.97	66.42	17.17	8.97
7	63.95	7.39	21.53	63.95	7.39	21.53	63.98	8.07	20.71
8	69.47	11.27	20.50	69.47	11.27	20.50	69.47	11.27	20.50
9	71.25	7.50	16.22	71.25	7.50	16.22	71.20	6.12	16.35
10	58.84	19.63	10.06	58.84	19.63	10.06	58.84	19.63	10.06
b) e skin colour measurement CIE L*a*b* values against white background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	55.54	3.98	17.50	55.54	3.98	17.50	55.54	3.98	17.50
2	43.03	9.01	14.52	43.03	9.01	14.52	43.03	9.01	14.52
3	77.26	3.30	9.30	77.26	3.30	9.30	77.26	3.30	9.30
4	44.11	7.57	16.89	44.11	7.57	16.89	44.11	7.57	16.89
5	67.18	7.83	22.42	66.10	7.92	23.52	66.10	7.92	23.52
6	66.42	17.17	8.97	66.40	17.68	9.65	66.40	17.68	9.65
7	63.95	7.39	21.53	63.95	7.39	21.53	63.95	7.39	21.53
8	69.47	11.27	20.50	69.47	11.27	20.50	69.47	11.27	20.50
9	71.25	7.50	16.22	71.25	7.50	16.22	71.18	7.19	17.02
10	58.84	19.63	10.06	58.84	19.63	10.06	58.84	19.63	10.06

Appendix 2. CIE L*a*b* colour measurements obtained with the test instrument – RGB colorimeter – at 25mm from the target against **a)** black and **b)** white background.

a) RGB Colorimeter CIE L*a*b* values at 25mm against a black background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	68.0	2.0	9.0	70.0	2.0	10.0	71.0	2.0	9.0
2	63.0	15.0	22.0	67.0	16.0	24.0	64.0	16.0	23.0
3	82.0	0.0	6.0	85.0	0.0	6.0	86.0	1.0	7.0
4	58.0	14.0	24.0	62.0	16.0	29.0	61.0	15.0	28.0
5	78.0	1.0	5.0	79.0	0.0	6.0	79.0	0.0	6.0
6	69.0	32.0	23.0	70.0	32.0	21.0	72.0	31.0	22.0
7	74.0	2.0	7.0	78.0	2.0	13.0	76.0	2.0	10.0
8	80.0	8.0	16.0	81.0	8.0	17.0	81.0	3.0	13.0
9	78.0	1.0	8.0	81.0	1.0	8.0	82.0	1.0	7.0
10	67.0	37.0	25.0	68.0	36.0	23.0	67.0	34.0	22.0
b) RGB Colorimeter CIE L*a*b* values at 25mm against a white background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	64.0	2.0	9.0	65.0	2.0	10.0	62.0	2.0	8.0
2	61.0	14.0	22.0	62.0	13.0	22.0	56.0	13.0	21.0
3	79.0	1.0	4.0	83.0	0.0	3.0	79.0	1.0	3.0
4	55.0	15.0	24.0	57.0	16.0	25.0	57.0	10.0	18.0
5	75.0	1.0	5.0	76.0	1.0	5.0	72.0	1.0	2.0
6	66.0	34.0	22.0	68.0	36.0	23.0	67.0	31.0	20.0
7	69.0	2.0	8.0	73.0	3.0	12.0	67.0	3.0	8.0
8	80.0	2.0	13.0	79.0	6.0	15.0	77.0	7.0	13.0
9	76.0	2.0	9.0	75.0	2.0	9.0	72.0	2.0	8.0
10	62.0	37.0	22.0	64.0	37.0	24.0	62.0	35.0	21.0

Appendix 3. CIE L*a*b* colour measurements obtained with the test instrument – RGB colorimeter – at 30mm from the target against **a)** black and **b)** white background.

a) RGB Colorimeter CIE L*a*b* values at 30mm against a black background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	67.0	2.0	8.0	65.0	3.0	7.0	66.0	3.0	7.0
2	59.0	12.0	22.0	59.0	11.0	19.0	60.0	11.0	19.0
3	80.0	1.0	4.0	80.0	1.0	4.0	79.0	1.0	4.0
4	60.0	8.0	17.0	58.0	8.0	17.0	56.0	7.0	13.0
5	74.0	1.0	5.0	74.0	1.0	3.0	73.0	1.0	3.0
6	70.0	25.0	21.0	72.0	27.0	21.0	71.0	25.0	20.0
7	74.0	3.0	8.0	71.0	3.0	6.0	72.0	3.0	8.0
8	80.0	3.0	9.0	81.0	1.0	9.0	78.0	3.0	10.0
9	76.0	1.0	6.0	75.0	1.0	4.0	75.0	1.0	6.0
10	66.0	32.0	19.0	66.0	32.0	19.0	64.0	33.0	19.0

b) RGB Colorimeter CIE L*a*b* values at 30mm against a white background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	52.0	3.0	10.0	54.0	4.0	12.0	55.0	4.0	12.0
2	47.0	15.0	22.0	48.0	14.0	19.0	47.0	15.0	20.0
3	74.0	1.0	4.0	74.0	2.0	3.0	74.0	1.0	3.0
4	49.0	16.0	25.0	49.0	15.0	24.0	50.0	16.0	25.0
5	64.0	3.0	7.0	64.0	3.0	7.0	65.0	3.0	5.0
6	66.0	27.0	16.0	65.0	29.0	17.0	65.0	29.0	17.0
7	60.0	8.0	18.0	60.0	7.0	13.0	60.0	7.0	14.0
8	71.0	9.0	18.0	72.0	7.0	16.0	71.0	7.0	16.0
9	68.0	6.0	12.0	70.0	4.0	10.0	70.0	5.0	10.0
10	60.0	31.0	17.0	61.0	31.0	17.0	60.0	31.0	17.0

Appendix 4. CIE L*a*b* colour measurements obtained with the test instrument – RGB colorimeter – at 35mm from the target against **a)** black and **b)** white background.

a) RGB Colorimeter CIE L*a*b* values at 35mm against a black background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	69.0	3.0	11.0	64.0	4.0	12.0	64.0	3.0	12.0
2	61.0	17.0	26.0	55.0	19.0	25.0	56.0	19.0	25.0
3	81.0	1.0	8.0	80.0	1.0	7.0	81.0	1.0	7.0
4	60.0	16.0	30.0	58.0	14.0	26.0	54.0	9.0	20.0
5	75.0	4.0	9.0	75.0	3.0	8.0	74.0	4.0	9.0
6	69.0	32.0	24.0	67.0	33.0	22.0	67.0	33.0	22.0
7	74.0	5.0	14.0	69.0	5.0	13.0	73.0	6.0	15.0
8	78.0	11.0	24.0	73.0	10.0	20.0	73.0	9.0	20.0
9	81.0	2.0	11.0	75.0	2.0	11.0	76.0	2.0	11.0
10	64.0	36.0	25.0	62.0	34.0	22.0	62.0	35.0	22.0

b) RGB Colorimeter CIE L*a*b* values at 35mm against a white background									
Swatch ID	L1	a1	b1	L2	a2	b2	L3	a3	b3
1	54.0	4.0	15.0	54.0	4.0	14.0	51.0	4.0	11.0
2	46.0	16.0	22.0	46.0	15.0	22.0	43.0	14.0	21.0
3	76.0	2.0	7.0	75.0	2.0	5.0	72.0	2.0	5.0
4	47.0	16.0	27.0	47.0	16.0	27.0	45.0	15.0	24.0
5	64.0	6.0	11.0	63.0	6.0	11.0	60.0	5.0	9.0
6	67.0	28.0	18.0	66.0	29.0	18.0	62.0	30.0	17.0
7	60.0	10.0	19.0	64.0	10.0	20.0	65.0	11.0	21.0
8	71.0	13.0	24.0	71.0	13.0	24.0	63.0	13.0	24.0
9	66.0	6.0	13.0	72.0	7.0	13.0	68.0	6.0	11.0
10	57.0	30.0	16.0	60.0	30.0	17.0	56.0	30.0	17.0